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Seismic scattering and absorption mapping of debris flows, feeding paths, and tectonic units at Mount St. Helens volcano

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ABSTRACT

Frequency-dependent peak-delay times and coda quality factors have been used jointly to separate seismic absorption from scattering quantitatively in Earth media at regional and continental scale; to this end, we measure and map these two quantities at Mount St. Helens volcano. The results show that we can locate and characterize volcanic and geological structures using their unique contribution to seismic attenuation. At 3 Hz a single high-scattering and high-absorption anomaly outlines the debris flows that followed the 1980 explosive eruption, as deduced by comparison with remote sensing imagery. The flows overlay a NNW–SSE interface, separating rocks of significant varying properties down to 2–4 km, and coinciding with the St. Helens Seismic Zone. High-scattering and high-absorption anomalies corresponding to known locations of magma emplacement follow this signature under the volcano, showing the important interconnections between its feeding systems and the regional tectonic boundaries. With frequency increasing from 6 to 18 Hz the NNW–SSE tectonic/feeding trends rotate around an axis centered on the volcano in the direction of the regional-scale magmatic arc (SW–NE). While the aseismic high-scattering region WSW of the volcano shows no evidence of high absorption, the regions of highest-scattering and absorption are consistently located at all frequencies under either the eastern or the south-eastern flank of the volcanic edifice. From the comparison with the available geological and geophysical information we infer that these anomalies mark both the location and the trend of the main feeding systems at depths greater than 4 km.

1. Introduction

Seismic attenuation measurements provide complementary information to velocity tomography on the state of volcanic media, thereby increasing our insight into their complex structure and composition. Knowing the mechanism with which seismic waves lose their energy in space, time, and frequency in the volcanic crust (either scattering or absorption) is crucial to improve seismic images of feeding paths and tectonic structures. The lateral variations in seismic attenuation induced by these two mechanisms can be quantified by (*1*) the peak-delay time of shear waves, defined as the lapse-time corresponding to the maximum of the seismogram envelope and (*2*) the coda quality factor Q_c, which quantifies the decay rate of the coda envelope with increasing lapse-time (Takahashi et al., 2007; Sato et al., 2012; Calvet et al., 2013; Prudencio et al., 2015).

Researchers were able to illuminate tectonic structures by mapping these two quantities, as done e.g. by Calvet et al. (2013) in the Pyrenean mountain range. Takahashi et al. (2007) have shown that peak-delay times increase as a consequence of strong forward scattering when seismic waves cross quaternary volcanoes embedded in the Japanese crust. Also in Japan, Carcolé and Sato (2010) have obtained high-resolution maps of seismic scattering and absorption by using the Multiple Lapse Time Window Analysis method (Fehler et al., 1992; Del Pezzo and Bianco, 2010). Their results demonstrate that the spatial variations of intrinsic absorption and Q_c at sufficient lapse-times from the origin time of the earthquake are highly correlated. At both regional and continental scale systematically higher peak-delay times and lower Q_c measurements therefore mark the most highly heterogeneous and absorbing structures.

We measure peak-delay times and Q_c to map frequency-dependent lateral variations of *S* wave scattering and absorption in the highly-heterogeneous crust under Mount St. Helens volcano

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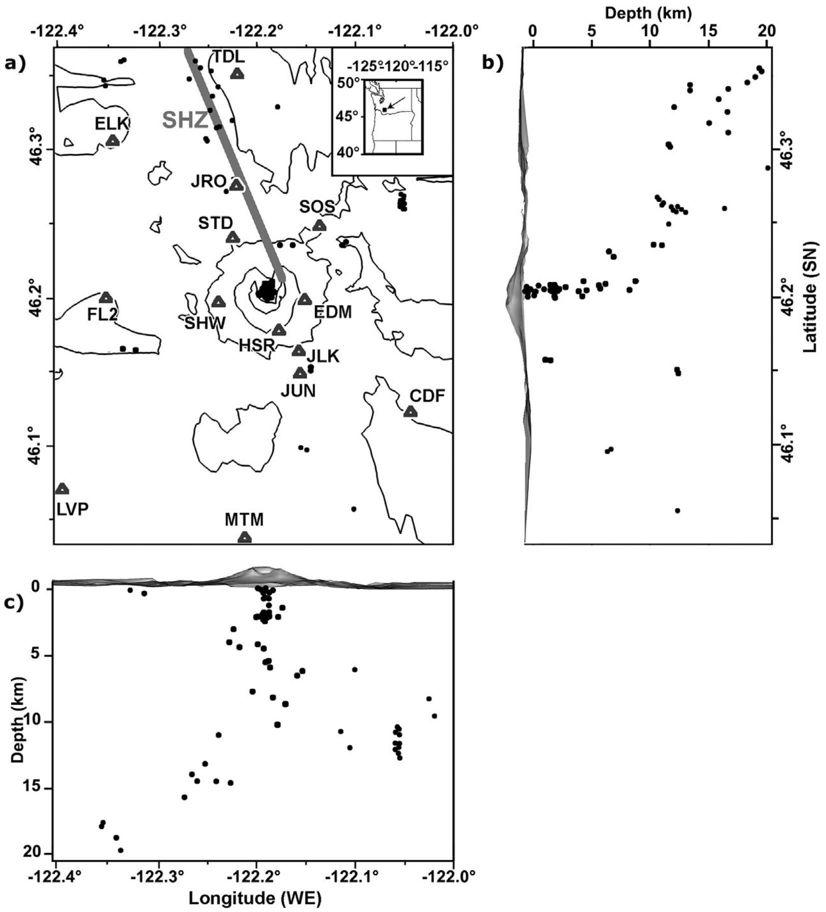

Fig. 1. Seismic and geographical data. (a) A map-view plot of the permanent network stations (gray triangles and letters with white contours), recording seismicity (black circles) between 2000 and 2003 at Mount St. Helens (MSH) on topography contoured at 1 km intervals. The color map shows the tomographically defined 2D *P* wave scattering (ε) spatial variations. The inset (upper right corner of the map) shows the location of MSH in southern Washington. We represent the St. Helens Seismic Zone (SHZ) as a thick black line on the map. Two vertical sections running south–north (b) and west–east (c) and including topography show the projected seismicity.

(hereafter MSH). We follow an approach similar to that of Calvet et al. (2013) to separate seismic scattering from seismic absorption. The only modification is that we measure *S* wave peak-delay times with respect to the *P* wave arrival. Our main assumptions are that (*1*) absorption strongly affects late lapse-time Q_c measurements and (*2*) peak-delay times and Q_c sensitivities are distributed uniformly along the 3D seismic ray (Calvet et al., 2013). The results of statistical analyses and the knowledge provided by geophysics, geology, and remote sensing in this well known area (see, e.g., De Siena et al. (2014) for a complete review) will shed light on the effects that different Earth media produce on coda intensities. The outcomes will both improve our understanding of how heterogeneous structures influence coda waves and give us a novel way to depict volcanic media at different scales, from shallow debris flows and geological units to deep feeding and tectonic systems.

2. Materials and methods

2.1. Data and P wave seismic heterogeneity

We use 451 high-quality vertical velocity waveforms produced by 64 earthquakes with magnitudes between 1.5 and 2.7 located around MSH (Fig. 1a–c). The waveforms are recorded at 13 stations of the Pacific Northwest Seismic Network between 2000 and 2003, before the explosive eruption of the volcano in 2004 (Fig. 1a). Hypocentral distances of lengths spanning between 5 and 60 km are measured along the seismic rays, traced using a Thurber-modified ray-bending approach in the velocity model of Waite and Moran (2009). After the deconvolution from the instrument response the seismograms are filtered in 4 frequency bands (2–4 Hz, 4–8 Hz, 8–16 Hz, 16–32 Hz). We compute the root mean square (*rms*) of the velocity waveforms and smooth the time series with a moving time-window whose duration is twice the central period of each frequency band. Finally, we calculate the seismic envelopes/intensities as the sum of the rms and of its Hilbert transform.

Using the velocity model of Waite and Moran (2009) we also obtain a 2D map of the *rms* of the *P* wave velocity fluctuations (Fig. 2a, ε), a direct measurement of *P* wave heterogeneity, following the approach described by De Siena et al. (2011). An exponential autocorrelation functions (ACF) is calculated using the *P* wave velocity tomograms (Waite and Moran, 2009) as measurements of the velocity wave field from the surface to depths of 10 km, in the regions of maximum resolution. To remove the depth dependence we fit the 21 vertical high-resolution (0.5 km depth slices) velocity measurements obtained at each point of the 2D map (Fig. 1a) by a Nth order average polynomial $V(z) = a_0^* + a_1^* z + a_2^* z^2 + \ldots + a_N^* z^N$. Assuming identical variances for the depth-dependent measurements we obtain the degree $N = 4$ of the polynomial and its coefficients a^* by using the Schwartz information criterion. The mean squared velocity fluctuations (ε^2) are estimated by measuring the maximum of the ACF obtained after detrending for this polynomial (De Siena et al., 2011). We will only discuss the points of the velocity model where we obtain random velocity fluctuations with a Lilliefors (Kolmogorov–Smirnov) normality test at a 5% significance